Inclusive dijet photoproduction and the resolved photon at THERA

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Abstract

A future ep facility, THERA, where electrons of 250 GeV and protons of 920 GeV are collided could provide valuable information on the structure of the photon. With an increase in the centre-of-mass energy of a factor of 3 and an extension of the minimum photon energy fraction carried by the interacting parton of a factor of 10 compared to HERA, a new kinematic regime in the study of the photon will be opened. Inclusive dijet production has been studied and the potential gains the new collider would bring are discussed. The differences between current parametrisations of the photon structure in this new kinematic region are shown to be up to 50%. Comparisons of THERA's capabilities are made with what HERA can currently produce and how it complements e^+e^- colliders addressed.

1 Introduction

Using the proton accelerator ring from HERA and the lepton accelerator chain for the proposed linear collider, TESLA, a centre-of-mass energy for ep collisions of ~ 1 TeV could be achieved [1]. The proposed facility, THERA, using protons of 920 GeV and leptons of 250 GeV would, due to the increase in lepton beam energy, greatly extend the kinematic regime currently accessible to HERA [1, 2].

The measurement of jet photoproduction in ep collisions allows the structure of the photon, emitted from the incoming lepton, to be probed. In Leading Order (LO) quantum chromodynamics (QCD), two types of processes contribute to jet photoproduction: the direct photon process, in which the photon itself interacts with a parton from the proton and the resolved photon process in which the photon acts as a source of partons, one of which interacts with a parton from the proton. Examples of these processes are shown in Fig. 1, where Fig. 1a shows the boson-gluon fusion direct process and Fig. 1b gluon-gluon fusion resolved process. As can be seen from Fig. 1, photoproduction processes depend on both the structure of the photon and proton; the cross-section, $d\sigma_{\gamma p\to cd}$ for the production of two partons being,

$$d\sigma_{\gamma p\to cd} = \sum_{ab}\int_{x_p} dx_p \int_{x_\gamma} dx_\gamma f_{p\to b}(x_p,\mu^2) f_{\gamma\to a}(x_\gamma,\mu^2) d\hat{\sigma}_{ab\to cd}, \quad (1)$$

where $f_{p\to b}(x_p,\mu^2)$ describes the proton parton density of a parton of momentum fraction, x_p, $f_{\gamma\to a}(x_\gamma,\mu^2)$ the photon parton density of a parton of momentum fraction, x_γ, both at some renormalisation and factorisation scale, μ^2, and $d\hat{\sigma}_{ab\to cd}$ is the perturbatively calculable short distance cross-section. As next-to-leading (NLO) order programs reasonably describe jet production, one can choose a region of phase space where the proton structure is well constrained and the only uncertainty, as can be seen in Eq. 1, is then the photon structure function. It is noted (although not studied further) that dijet production at HERA and THERA could also provide information on the proton structure using high transverse energy or (very) forward jets. This would provide information on the parton densities at high values of x_p at large scales, as in $p\bar{p}$ collisions, which are not well constrained by the F_2^p DIS measurements.

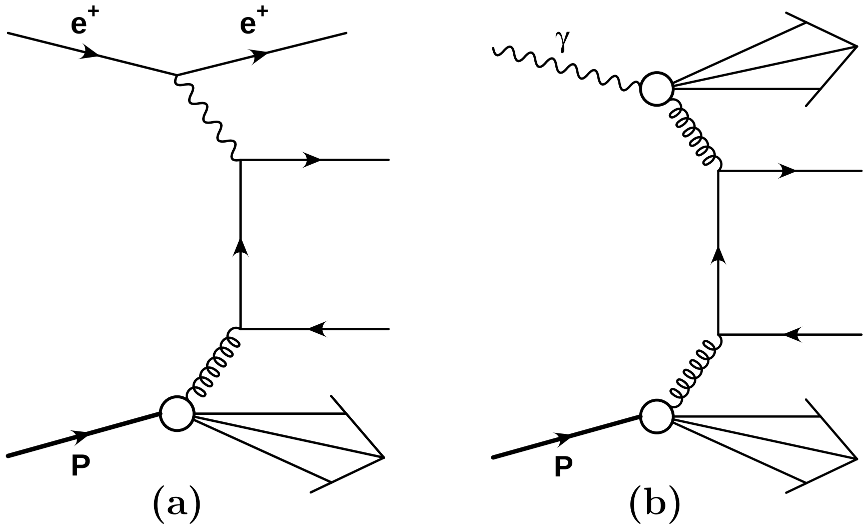


Figure 1: Examples of LO (a) direct photon and (b) resolved photon processes in ep collisions.

Measurements of the photon structure function, F_2^γ, at e^+e^- experiments have constrained the quark density in the region $10^{-3} < x_\gamma < 0.5$ [6]. Photoproduction can provide further constraints on the quark density at high x_γ and on the gluon density at all x_γ. In jet photoproduction, unlike in e^+e^- scattering, there is direct access to the gluon density in the photon at LO. The poorly constrained gluon density is expected to become more significant with decreasing x_γ. Measurements have been made at HERA, which probe these uncertain parts of the structure of the photon [7, 8, 9, 10]. An electron beam energy of a factor of 10 higher for THERA than for HERA gives an extension in the minimum x_γ also by a factor of 10 [2]. THERA would lead to an extension of the kinematic range into a region where accurate measurements of the gluon density could be made and the rise in the structure function, F_2^γ, thoroughly tested.

2 Photoproduction from HERA to THERA

Currently at HERA, the highly asymmetric beam energies provide problems in measuring resolved photon processes. In general, there is a strong tendency for events to be very forward in the proton beam direction. This means that many events fall outside the acceptance of the current detectors or are mixed up with the proton remnant making their measurement difficult. This is particularly acute in the case of resolved photon processes in which jets are generally produced in the forward direction; direct photon processes generally being central. The reduced asymmetry THERA would provide will significantly change the topology of photoproduction events. Direct photon events would then be concentrated in the rear direction and resolved photon processes in the central and forward parts of the detector. This would then increase the acceptance for resolved photon events and hence improve the measurements.

Measurements of dijet photoproduction at HERA can be (somewhat artificially) categorised into those with low transverse energy jets, low$-E_T^{\rm jet}$, and those with high$-E_T^{\rm jet}$ which start at around 5 GeV and 10 GeV, respectively. The advantage of the low$-E_T^{\rm jet}$ measurements is the increased resolved photon cross section, in particular at low$-x_\gamma$. The measurements suffer, however, from a lack of understanding of soft underlying physics which either leads to results with large systematic uncertainties or inconclusive comparisons with theory. At high$-E_T^{\rm jet}$, the effect of soft underlying physics is greatly reduced, but so is the resolved cross section at low$-x_\gamma$.

This can be seen by considering the observable $x_\gamma^{\rm obs}$, which is the fraction of the photon's energy producing the two jets of highest transverse energy [3];

$$x_\gamma^{\rm obs} = \frac{E_T^{\rm jet1} {\rm e}^{-\eta^{\rm jet1}} + E_T^{\rm jet2} {\rm e}^{-\eta^{\rm jet2}}}{2yE_e}, \quad (2)$$

where $\eta^{\rm jet}$ is the pseudorapidity of the jet and E_e is the electron energy and y the fraction of the electron's energy carried by the photon.

Recent results from HERA are shown for low$-E_T^{\rm jet}$ events ($E_T^{\rm jet} > 6$ GeV) in Fig. 2a and for high$-E_T^{\rm jet}$ events ($E_T^{\rm jet} > 14$ GeV) in Fig. 2b. Shown are the detector-level distributions for $x_\gamma^{\rm obs}$ compared to Monte Carlo (MC) models. In Fig. 2a, the data is compared to MC models with and without multiparton interactions (MPI). Here it can be seen that the MC without MPI greatly underestimates the data at low$-x_\gamma^{\rm obs}$, and that a significantly increased cross-section is observed in the MC with the inclusion of MPI. The data is, however, still poorly described by the MC at this low$-x_\gamma^{\rm obs}$ region for jets of low$-E_T^{\rm jet}$. In Fig. 2b, the data compares well, over the full $x_\gamma^{\rm obs}$ range, with MC models containing no MPI, due to the increased $E_T^{\rm jet}$. The significant decrease in the number of low$-x_\gamma^{\rm obs}$ events at high$-E_T^{\rm jet}$ is also apparent.

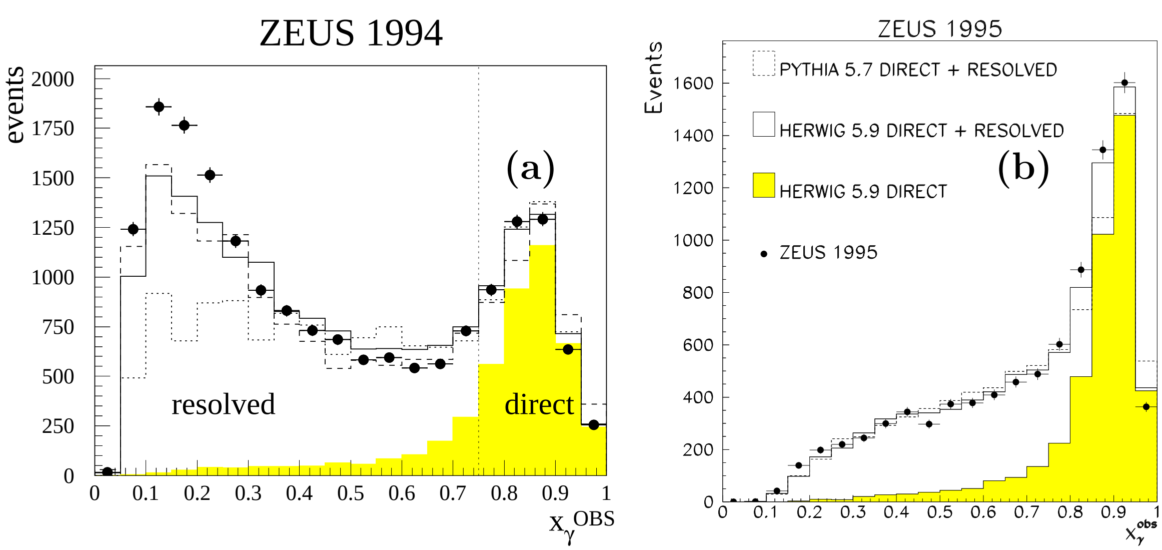


Figure 2: Detector-level distributions of $x_\gamma^{\rm obs}$ at HERA for (a) $E_T^{\rm jet} > 6$ GeV and (b) $E_T^{\rm jet} > 14$ GeV. In (a), the data points are compared to Herwig MC [4] with (solid line) and without (dotted line) multiparton interactions and Pythia MC [5] predictions also with multiparton interactions (dashed line). In (b), the data points are compared to Herwig MC (solid line) and Pythia MC (dashed line) predictions, both without multiparton interactions. In both (a) and (b) the shaded histogram indicates the contribution from direct photon processes in Herwig.

With the increased lepton beam energy THERA could provide the optimum scenario in which measurements could be made at relatively high$-E_T^{\rm jet}$ and low$-x_\gamma^{\rm obs}$.

3 Cross section definition

A realistic approach has been performed to evaluate the extent to which dijet production at THERA can yield new information on the structure of the photon. Therefore a kinematic range has been considered which could possibly be measured rather than choosing the full phase space. The kinematic region is based on a high$-E_T^{\rm jet}$ measurement from the ZEUS collaboration [8, 9].

To define the region to be photoproduction, a value of the photon virtuality, Q^2, of less than 1 GeV^2 has been applied. Currently at HERA, the requirement that the scattered lepton is not seen in the calorimeter implicitly leads to the condition on the photon virtuality. To achieve the same Q^2 requirement with the increased lepton beam energy, the angle of scatter will be much smaller. This would mean that the calorimeter (or some other detector) would need to be positioned very close (in fact to within $\sim 0.5^\circ$) to the beam-pipe in the rear direction to achieve the same Q^2 requirement using the anti-tag condition. The inelasticity, y, is chosen to be within the region, $0.2 < y < 0.85$, which corresponds to a photon-proton centre-of-mass energy of between 429 GeV and 884 GeV. The jets are required to have transverse energies, $E_T^{\rm jet1,2} > 14, 11$ GeV in the region of pseudorapidity, $-1 < \eta^{\rm jet} < 2$. Increasing the cut on the transverse energy was also considered. Allowing the jets to go more forward in pseudorapidity would increase the resolved photon cross section and would hopefully be possible depending on the detector configuration. At HERA where the proton beam energy is very much greater than the lepton beam energy, there are very few jets with a pseudorapidity less than -1. At THERA the distribution of jets would be more symmetric in pseudorapidity and relaxing this cut to, say -2 or -2.5 would also be an option. For this analysis, the value of -1 is retained to try and enhance the (more forward going) resolved photon component in a part of phase space which could definitely be measured. Extension and modification of these requirements could be considered in future studies.

For studying the potential of ep collisions at ~ 1 TeV, the cross sections were produced using NLO code from Frixione and Ridolfi [11]. As the proton structure function is well constrained in the region of x_p under study (approximately $10^{-2} < x_p < 10^{-1}$), only the CTEQ-4M [12] parton distribution function was considered. The renormalisation and factorisation scales, μ, were set to be equal to $E_T^{\rm jet1}$. To test the sensitivity of the cross sections, three photon parton density parametrisations were used; GS96-HO [13], GRV-HO [14] and AFG-HO [15]. Jets are defined using the longitudinally invariant k_T-clustering algorithm [16] in the inclusive mode [17].

4 Results

The kinematic requirements for the analysis performed at HERA restrict the minimum $x_\gamma^{\rm obs}$ to be ~ 0.07, where both jets are of minimum transverse energy and have a pseudorapidity of 2. At THERA the minimum $x_\gamma^{\rm obs}$ is reduced by the same factor as the lepton beam energy is increased to ~ 0.008. Figure 3a shows the cross-sections in $x_\gamma^{\rm obs}$ for HERA and THERA for the kinematic region stated. At HERA, the events are concentrated at high$-x_\gamma^{\rm obs}$ arising predominantly from direct photon events. At THERA, the events are concentrated at low$-x_\gamma^{\rm obs}$ characteristic of resolved photon events, with a very small cross-section at $x_\gamma^{\rm obs}$>0.75 which is taken to be a direct photon enriched region. Having seen that THERA greatly improves the potential for studying the resolved photon, it is then interesting to see if the new kinematic region shows sensitivity to the current parametrisations of the structure of the photon. Results for the three different photon parton density parametrisations are shown in Fig. 3a and their relative difference in Fig. 3b. It can be seen that the prediction using the GS96-HO parametrisation gives the highest and using the AFG-HO parametrisation the lowest cross section. The prediction with GS96-HO is up to 35% higher than that of GRV-HO and 50% higher than that of AFG-HO at low$-x_\gamma^{\rm obs}$. The difference between the results based on the three parton density parametrisations decreases with increasing $x_\gamma^{\rm obs}$. It should be noted that at the lowest values of $x_\gamma^{\rm obs}$ shown here, there exist no measurements from LEP at the scale considered (~ 200 GeV^2).

As can be seen from Eq. 2, the minimum $x_\gamma^{\rm obs}$ increases with increasing $E_T^{\rm jet}$. The relative fraction of low to high$-x_\gamma^{\rm obs}$ and hence resolved photon to direct photon processes also decreases

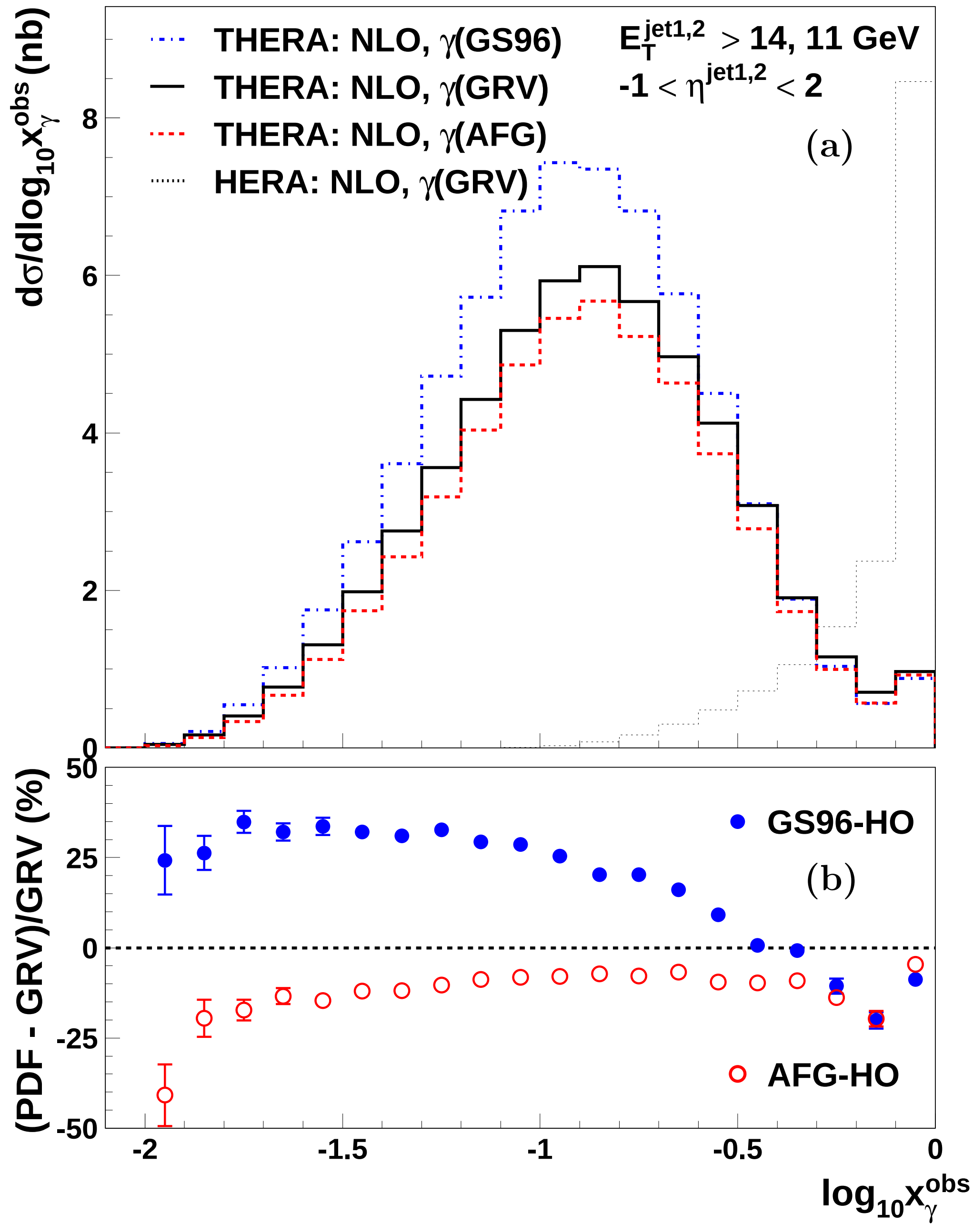


Figure 3: (a) The differential cross section, $d\sigma/d\log_{10}x_\gamma^{\rm obs}$ for inclusive dijet photoproduction at HERA and THERA as predicted by a NLO calculation. For the kinematic range, $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$ with two jets, $E_T^{\rm jet1,2} > 14, 11$ GeV and $-1 < \eta^{\rm jet} < 2$, the prediction for HERA using the GRV-HO photon parametrisation is shown as the dotted line. For THERA with the same kinematic cuts, three photon parton density parametrisations are shown; GS96-HO (dot-dashed line), GRV-HO (solid line) and AFG-HO (dashed line). In (b) the percentage differences in the cross-sections between the three predictions for THERA are shown as a function of $\log_{10}x_\gamma^{\rm obs}$. The relative difference of the predictions using GS96-HO (solid points) and AFG-HO (open points) with respect to GRV-HO is displayed.

with increasing $E_T^{\rm jet}$. Nevertheless, differences between the predictions with GS96-HO and AFG-HO are up still to 30% at a minimum cut-off in the transverse energy of the leading jet of 29 GeV.

Cross-sections as a function of the transverse energy of the leading jet, $E_T^{\rm jet1}$, in different regions of pseudorapidity of the jets are shown in Fig. 4. It is shown that the differences between the three predictions are concentrated at low$-E_T^{\rm jet1}$ and forward pseudorapidity. At more central and rear values of pseudorapidity and higher transverse energies, the predictions converge.

The cross-section as a function of the pseudorapidity of the second jet, $\eta_2^{\rm jet}$, is expected to be sensitive to the structure of the photon [8]. In Fig. 5, this cross section is shown in three regions of pseudorapidity of the first jet, $\eta_1^{\rm jet}$. Again, it can be seen that the predictions differ most significantly, up to 50%, when both jets are forward. It can also be seen that in the region where both jets are forward the direct photon enriched region, $x_\gamma^{\rm obs} > 0.75$, is negligible. As for the cross section in $x_\gamma^{\rm obs}$, the predictions for the GRV-HO and AFG-HO parametrisation are very similar in shape and differ in magnitude by roughly 10%. At higher transverse energies, $E_T^{\rm jet1} > 29$ GeV, a difference of 30% persists when both jets are forward.

To assess the significance of the differences observed between the predictions with the three different parametrisations, the renormalisation and factorisation scale uncertainties were evaluated. The cross sections using the GRV-HO parametrisation were calculated with the scale doubled and halved. For the cross-sections as a function of $\eta_2^{\rm jet}$, the relative differences to the central values are shown. The differences are of the order of $10-15\%$, which is small compared with the differences between the parametrisations. A difference of 15% was also observed for the cross-section as a function of $x_\gamma^{\rm obs}$.

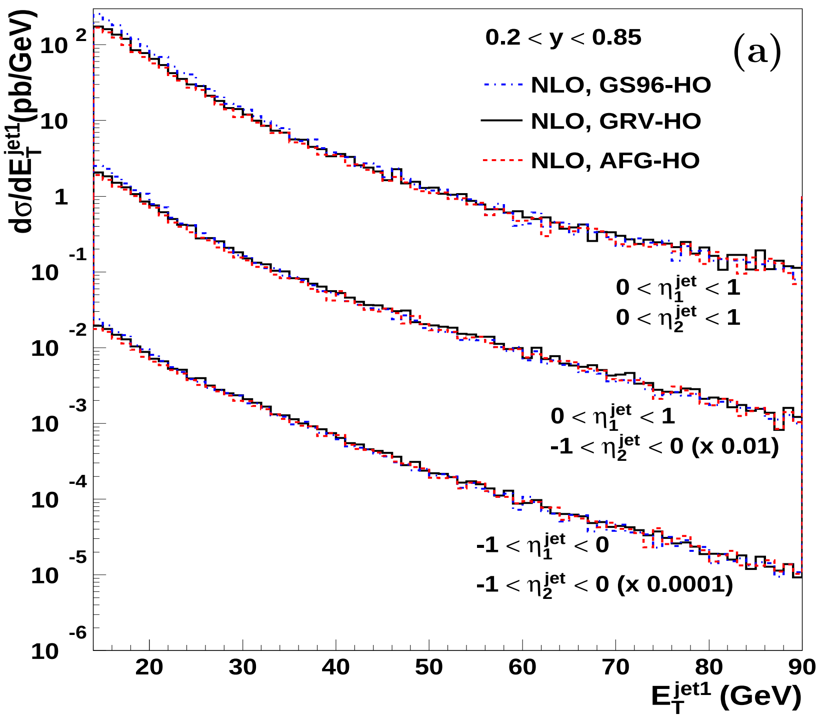
There exist many other calculations of jet photoproduction at HERA [18] all of which (including the one used in this article) have been shown to agree within $5-10\%$ [8, 19]. From this and the estimation of the scale uncertainty, it can be seen that the differences in the photon parton denisty parametrisations are much larger than other uncertainties.

5 Discussion

The potential of THERA with respect to what can be done at HERA and at LEP in the field of the photon structure is as follows. For a given transverse energy, it can achieve lower values of x_γ than is accessible at either of the current facilities. THERA would have the potential to measure the structure of the photon in the region where the structure function is predicted to rise with decreasing x_γ. Indications for the rise have be seen at LEP and HERA although the measurements have large errors. THERA would, however, be able to make more precise measurements by being able to achieve the factor of 10 smaller in the minimum $x_\gamma^{\rm obs}$ for a given $E_T^{\rm jet}$ compared with HERA. It has also been shown elsewhere that the accessible maximum average transverse energy of a dijet system is 2-3 times larger at THERA than at HERA with roughly 150 GeV and 225 GeV being reachable at the ep and γp options, respectively [20].

Forward detectors would also be desirable for measurements of the proton structure function at high x_p. For studying values of $x_p > 0.5$, for example, jets of $E_T^{\rm jet}$ greater than roughly 20 GeV would need to be detected at pseudorapidity values, $\eta^{\rm jet} = 3$. Jets of this energy would be produced copiously; considering those more central would require much larger energy.

Heavy quarks in dijet production have also been studied as a tool for constraining the structure of the photon and are discussed in detail elsewhere [21].



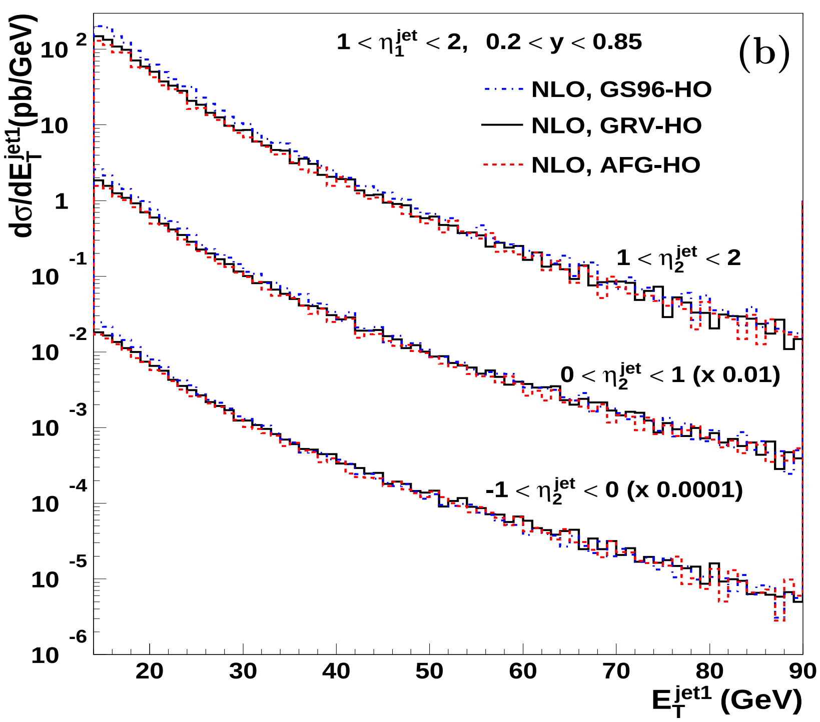


Figure 4: (a) The differential cross section, $d\sigma/dE_T^{\rm jet1}$ for inclusive dijet photoproduction at THERA as predicted by a NLO calculation. For the kinematic range as in Fig. 3, the prediction for THERA using three photon parton density parametrisations are shown; GS96-HO (dot-dashed line), GRV-HO (solid line) and AFG-HO (dashed line). The three different sets of curves represent jets in different regions of pseudorapidity. (b) The differential cross section, $d\sigma/dE_T^{\rm jet1}$ for inclusive dijet photoproduction at THERA as predicted by a NLO calculation when one jet is in the region $1 < \eta^{\rm jet1} < 2$ and the other jet is in three different regions of pseudorapidity.

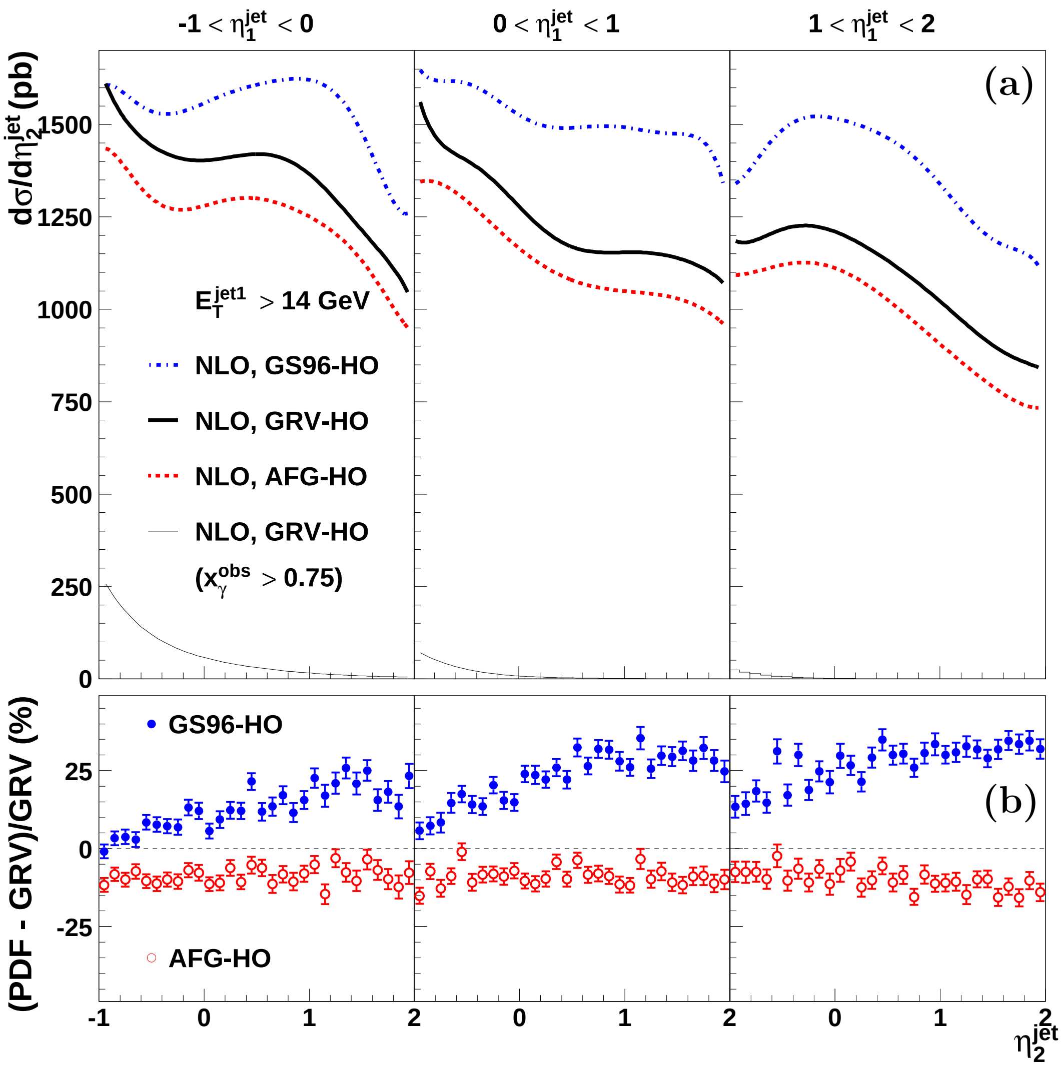


Figure 5: (a) The differential cross section, $d\sigma/d\eta_2^{\rm jet}$ for inclusive dijet photoproduction at THERA as predicted by a NLO calculation. For the kinematic range, $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$ with two jets, $E_T^{\rm jet1,2} > 14, 11$ GeV and $-1 < \eta^{\rm jet} < 2$, the prediction for THERA using three photon parton density parametrisations are shown; GS96-HO (dot-dashed line), GRV-HO (solid line) and AFG-HO (dashed line). One jet is restricted to be in a rear, central or forward direction. The prediction for $x_\gamma^{\rm obs} > 0.75$ is also shown as the thin solid line. In (b) the percentage differences in the cross-sections between the three predictions for THERA are shown as a function of $\eta_2^{\rm jet}$. The relative difference of the predictions using GS96-HO (solid points) and AFG-HO (open points) with respect to GRV-HO is displayed.

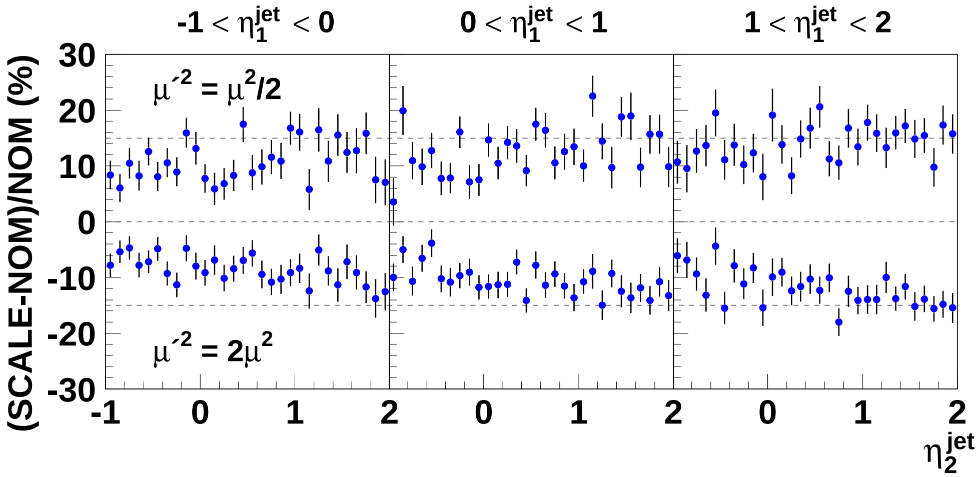


Figure 6: The percentage differences in the cross-sections from Fig. 5 when varying the renormalisation and factorisation scales by a factor of 0.5 and 2. The photon parton density parametrisation used was GRV-HO. The dashed line indicates ±15%.

With respect to the linear collider, TESLA, lower values of x_γ can also be reached at THERA but only at very forward values of pseudorapidity [2]. Development of a detector for THERA which can measure jets in the forward direction would therefore be very desirable. THERA would also complement a linear collider in the measurement of the structure of the photon in much the same way as HERA complements LEP; for example in directly constraining the gluon density and testing the universality of the parton distribution functions.

6 Summary

It has been shown that cross sections in the kinematic region open to THERA with a centre-of-mass energy of $\sim$ 1 TeV have a large sensitivity to the structure of the photon. Three currently available parametrisations lead to cross sections which vary by up to 50% in certain regions of the phase space considered. THERA would provide a new kinematic region in the measurement of the structure of the photon and complement measurements from the proposed linear collider.

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